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ACOUSTIC PROPERTIES OF PAPER AND PAPER-BASED PRODUCTS IN ARCHITECTURE

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ABSTRACT

The fundamental acoustic parameters of a component used in architecture describe its sound absorption or insulation properties. The first is symbolized by the absorption coefficient α - one of the basic parameters used in room acoustic. α represents the ratio of absorbed to incident sound energy and varies from 0 to 1, where 0 is a total reflection and 1 – total absorption.

The second – sound insulation – means the ratio of acoustic energy not transmitted through the material, thus reflected or absorbed. The parameters characterizing the insulation potentiality of the material are the Transmission Loss (TL) and Sound Reduction Index (R).

Both features depend on the frequency, although could be described by a single number. For instance: for absorption - Noise Reduction Index NRC (the average α for the octaves 250, 500, 1000, and 2000 Hz) and for insulation - Weighted Sound Reduction Index R_W (the weighted and averaged R). Nevertheless, when possible, both absorption and insulation should be judged in the full frequency range. Using only a single number of parameters can lead to serious complications, usually in a low-frequency band. This rule is even more crucial when considering the low-density products as paper.

This paper concerns the analysis of absorption and insulation properties of paper provided by the available literature.

1. Sound absorption of paper and paper-based products

The sound absorption coefficient could be measured by using several different methodologies. The laboratory ones can be divided into low-scaled such as Kundt's tube method or realistic-scaled as reverberant room measurement. The first one has some limitations corresponding to mentioned dimensions and plane wave use. The α values may differ in realistic conditions when the sound will income from every direction. For precise measurement, the reverberant room methodology is more adequate. Unfortunately, its use demand placing a sample with the dimension on the order of 10 m^2.

Cellulose fibre is an increasingly used absorbing material. Thus its acoustic absorption properties are well-researched for multiple cellulose types, such as cellulose spray [1], unbleached cellulose [2] or recycled cellulose [3]. Cellulose reaches the absorption efficiency of mineral-fibre-based products, commonly used in architecture. However, there is little to no information available about the α of paper and paper-based products. The reason lies in process of paper forming. Cellulose fibres are pressed and dried, which leads to creating a dense structure with clamped fibres. The friction cannot occur in such a structure as well as between unbonded fibres, hence, the absorption coefficient is too low to be a valuable research subject in the past. The results in Fig. 1 confirm the weak absorption of paper – in this case, corrugated cardboard. When the corrugated cardboard veins are facing the wave parallelly, the sound absorption can be enhanced [4].

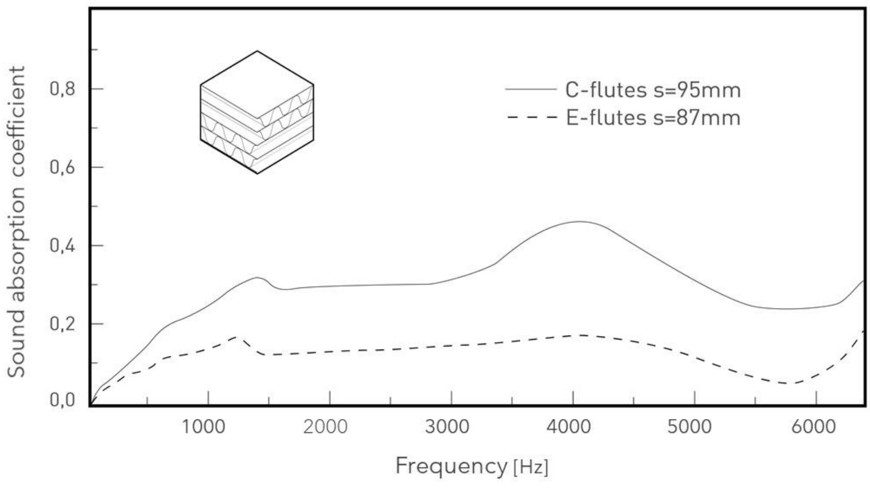

Fig. 1 Sound absorption coefficient of the multi-layered corrugated cardboard, with wave incident on a cover [5]

Nevertheless, the researchers find new solutions based on small modifications to the paper or employing paper as a component. Such solutions can achieve high sound absorption coefficient values.

Asdrubali et al. [5] suggested mounting paperboard as membrane panel. Such a structure can extinguish the energy of incident acoustic waves by transforming it into the resonance vibrations of the whole panel membrane. Membranes are frequently used in room acoustics to control low-frequency sound.

Kang, Kim, and Jang [6] utilized corrugated cardboard structures and simply formed small Helmholtz resonators with perforations in the panel. The resulting samples had increased absorbing and insulating parameters in the resonance frequencies. The peak absorption coefficient of a double panel reached 0,47 for the low frequency of 320 Hz and 0,68 for 1232 Hz.

Secchi et al. [7] proposed a similar idea. The cellulose fibre was covered with the perforated honeycomb panel. The opened honeycomb cells became the Helmholtz resonators and caused the α_S (measured in diffused field) to grow up to 1,2 for 500 Hz and to 1,0 for 2500 Hz.

M. Neri et al. [8] in their recent work analysed the possibilities of reusing end-of-life household materials, including paperboard, as a wall lining. Two samples contained a Helmholtz resonator formed with glued paperboard panels. The third was the double panel constructed with a paperboard with the absorptive filling. The result α reached 0,8 for certain frequencies in the range 400-2000 Hz.

2. Sound insulation of paper and paper-based products

Insulation properties (similarly to absorption) could be measured using low-scaled equipment such as Kundt’s tube (the Transmission Loss measurement) or realistic-scaled as the reverberant room (the Sound Reduction Index measurement). The limitations of techniques correspond to the ones mentioned in the previous paragraph. The additional flaw of Kundt's tube is the difficulty in the repeatability of the TL measurement, caused by the mounting of the sample. Validation that the test conditions are undifferentiated is crucial. The most reliable TL comparisons are those done within a single publication.

a. Transmission Loss measurements

Most available data on paper insulation is the TL results measured in the Kundt tube. The works of Asdrubali et al. [5] and Kang, Kim, and Jang [6] on corrugated cardboard as well as Ricciardi et al. [9] on waste paper and Neri et al. [8] on end-of-life materials clearly demonstrate, that high insulation properties could be reached by stacking multiple layers of paper or paper-based products. The TL of such measurement cannot be directly compared due to mentioned reasons. Nevertheless, the results for most insulating structures are high (in the order of 40 dB or above for frequencies in the range of 200 Hz to 2000 Hz) and thus can correspond to results of conventional materials with the same thickness. The results are even more promising, when realising low-surface mass of structures.

b. Sound Reduction Index prediction

Until now, the sound insulation analyses did not need to be conducted on final paper-based partitions, but rather during an early design stage. For such applications, Kundt's tube method was more practical. Consequently, the results of the Sound Reduction Index measurements of paper are not commonly accessible yet.

The only publication concerning the Sound Reduction Index of paper-based products focuses on analytical calculation. Secchi et al. [7] predicted R_W values of ten structures with the specialized software Insul®. Each structure has two to four different variants giving 24 specimens. Every specimen is rated based on the acoustic properties, cost, transport and lightness, and recyclability, with the grade: not convenient, medium, or convenient. The four most insulating products with a short description and comparison to conventional materials are presented in Table 1.

Table 1 R_W of most insulating structures, formed with paper-based products and compared to conventional, lighweight constructions

Product / Construction	**Description**	**R_W [dB]**	**Rating**
	Paper-based structures [7]		
3A Sandwich panel	Double perforated honeycomb panel (thickness: 15 mm) with cellulose filling (t: 50 mm) Cellulose fiber density – 50 kg/m^3	16	*Convenient*
4C Sandwich panel	Double perforated corrugated honeycomb panel (t: 15 mm) with filling of cellulose (t: 30 mm). Cellulose fiber density – 60 kg/m^3	16	*Convenient*
6A Paper tubes wall	Partition of paper tubes (thickness of wall: 10 mm) filled with cellulose fiber, with slits distributed on all tube. Cellulose fiber density – 50 kg/m^3	24	*Medium*
7B Paper tubes wall	Curved partition of paper tubes (thickness of wall: 5 mm) filled with cellulose fiber, with slits distributed on all tube. Cellulose fiber density – 80 kg/m^3	21	*Convenient*
	Conventional structures with lighweight construction		
Plasterboard	Single plasterboard panel. R_W calculated with Insul 9.0 ®. Surface mass – 9.6 kg/m^2	27	-
Double beaverboard [10]	Double beaverboard panel (t: 5 mm) with the filling of mineral wool (t: 50 mm). Surface mass – 20 kg/m^2	35	-

Paper-based products have a potential application as partitions. Nonetheless, to use it in architecture, they need to be improved to reach the R_W values of about 35 dB.

3. Summary

The data in the analysed literature enables to consider paper-based products as promising absorption and insulation material. To enhance the paper absorption properties, one can perform minor modifications (such as perforation or mounting paper as a membrane panel). High insulation is achievable, especially when stacking the paper-based panels in multiple layers. In such a form, even the lightweight construction can reach moderately high insulation. However, the structures still need to be improved to be used as partitions. The principal weakness of the available data is the research methodology. The majority of both absorption and insulation research is conducted under conditions that do not correspond to real applications. There is a substantial knowledge gap in data about insulation properties of common paper-based products.

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